VENTILATION RATES IN U.S. OFFICE BUILDINGS FROM THE EPA BASE STUDY

AK Persily[1*], J Gorfain[1], G Brunner[2]

1 Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg MD, USA
2 Indoor Environment Division, Office of Radiation and Indoor Air, U.S. Environmental Protection Agency, Washington DC, USA

ABSTRACT
The EPA BASE study involved indoor environmental measurements in 100 U.S. office buildings. This paper presents an analysis of the measured outdoor air ventilation rates, including comparisons with the requirements in ASHRAE Standard 62. The outdoor ventilation rates measured using duct traverses at the air handler intakes are higher than might be expected, with a mean value of about 55 L/s per person. However, these elevated values are not so unexpected given the low occupant density (mean of about 4 persons per 100 m^2) and the high outdoor air fractions (mean of about 35 %). Air change rates based on peak carbon dioxide concentrations in the space are lower than the volumetric values with a mean of about 20 L/s per person. Questions exist regarding the reliability of these peak CO_2 values based on the validity of the assumptions on which the determinations are based.

INDEX TERMS
carbon dioxide, database, measurement, office buildings, ventilation,

INTRODUCTION
The U.S. Environmental Protection Agency (EPA) Building Assessment Survey and Evaluation (BASE) study was conceived to address the indoor air quality (IAQ) data gap in public and commercial office buildings. As described in the protocol for the study (EPA 2003), the primary goal was to define the status of the existing building stock with respect to determinants of IAQ and occupant perceptions. The study protocol incorporated three major areas: comfort and environmental measurements; building and HVAC characterization; and an occupant questionnaire. While certain aspects of the entire building were characterized, one or more representative sampling spaces (referred to as *study spaces*) in each building were more intensively characterized. Ventilation performance was a key part of the BASE study, and this paper presents an analysis of the measured outdoor ventilation data. There have been previous analyses of the building and HVAC data, as well as some papers describing the BASE study in more general terms (Brightman et al. 1996, Womble et al. 1995 and 1996). Apte et al. (2000) and Erdman et al. (2002) examined associations between sick building syndrome symptoms and indoor-outdoor CO_2 concentration differences as surrogates for per person ventilation rates.

The National Institute of Standards and Technology (NIST) analyzed the BASE ventilation data with respect to ventilation system design and performance. In addition NIST evaluated the BASE protocol with respect to its ability to obtain reliable ventilation performance data and recommended modifications to the protocol for use in future studies. The NIST analysis focused on the following parameters: supply airflow, outdoor air fraction, outdoor air ventilation, and exhaust airflow. This paper discusses only the outdoor air ventilation results. A more thorough presentation of the NIST study is contained in Persily and Gorfain (2004).

RESEARCH METHODS
Outdoor air ventilation rates in the study spaces were determined in a number of different ways, as described below, employing the following measurements. An uncertainty analysis was performed for each derived parameter based on propagation of the uncertainty estimates of the measured quantities as described in Persily and Gorfain (2004). Supply, recirculation and outdoor air intake airflows were measured for the air handlers serving each study space using standard duct traverse techniques. These three airflows were generally measured twice a day in each building, generally in the morning and afternoon on the Wednesday and Thursday of the study week. At those times, carbon dioxide (CO_2) concentrations were also measured in the supply, recirculation and outdoor air to determine the

* Corresponding author email: andyp@nist.gov

outdoor air fraction. CO_2 concentrations in the occupied space were monitored continuously with fixed monitors, several of which were deployed in each study space and recorded the concentration every 5 min over several days.

Outdoor air intake was determined for individual air handlers using whichever of the following approaches was possible:

Direct measurements of the volumetric airflow in the outdoor air intake duct.
Difference between the measured supply and recirculation volumetric airflows.
Outdoor air fraction based on CO_2 (see Equation (1)) multiplied by the supply airflow.

These outdoor air intake values were then used to determine the outdoor airflow to each study space based on the fraction of the air handler airflow delivered to the study space. Ventilation rates determined by either of first two methods are referred to as *volumetric*, and those determined with the third are referred to as *CO_2 ratio*. In determining the outdoor air intake through multiplication of the supply airflow by the outdoor air fraction F_o, these fractions were determined from the measured CO_2 concentrations in the outdoor, supply and recirculation airstreams using Equation (1),

$$F_o = (C_R - C_S) / (C_R - C_O) \qquad (1)$$

where C_R, C_S and C_O are the CO_2 concentrations in the recirculation, supply and outdoor air respectively.

The outdoor air ventilation in the study space was also estimated based on the indoor CO_2 concentrations measured with fixed monitors. The concentrations were averaged across the study space and the peak value identified. In some cases there was both a morning and an afternoon peak; in other cases, only a single peak was determined for the day. The peak concentration minus the corresponding outdoor concentration was then used to estimate the outdoor airflow per person assuming that the CO_2 concentration is at equilibrium and a CO_2 generation rate per person of 0.0052 L/s. This method, referred to as *peak CO_2*, is based on a single-zone mass balance of CO_2 and therefore is valid only when the concentration is indeed at steady-state. In addition, this approach assumes the concentration is uniform throughout the space, airflows from adjoining spaces can be ignored, and the outdoor concentration, ventilation rate and generation rate are all constant (Persily 1997). Since the validity of these assumptions was not investigated as part of this study (except the outdoor concentration was monitored), the validity of the results obtained is subject to question.

RESULTS

Table 1 summarizes the measured outdoor air ventilation to the study spaces for the three methods. They are presented on a per person basis using the actual number of occupants during each measurement and on a per workstation basis, with the latter reflecting the per person rates if the spaces were fully occupied. On average, the study spaces were occupied at 80 % during the ventilation measurements, based on the number of workstations. The mean volumetric value is 55 L/s per person, which is high relative to the 10 L/s per person value specified in many current building codes (based on ASHRAE Standard 62-2001). Of these per person values, 17 % are below 10 L/s per person and 9 % are below 5 L/s.

Table 1. *Summary of Measured Outdoor Air Ventilation Rates*

	Volumetric	**CO_2 Ratio**	**Peak CO_2**	**Volumetric**	**CO_2 Ratio**	**Peak CO_2**
	L/s per person			L/s per workstation		
Mean	55	49	22	40	35	17
25^{th} percentile	13	12	13	10	10	10
Median	30	31	18	21	22	14
75^{th} percentile	68	63	25	53	47	19

While the mean per person rate (volumetric) appears to be higher than expected, note that over 70 % of the BASE study spaces had air handlers equipped with economizers to provide "free-cooling" by increasing outdoor airflow during mild weather. A significant number of the measurements occurred during mild outdoor air temperatures, resulting in an average outdoor air fraction of nearly 40 %, compared with 10 % to 20 % outdoor air that is typical under minimum intake conditions. Measured outdoor air rates were identified for which the outdoor air fraction was below 20 %, presuming that those values correspond to operation at or near minimum outdoor air intake. The mean of these values is 13.7 L/s per person based on the measured number of occupants, and the mean based on the number of workstations is 10.5 L/s. Forty-one percent of the per person values are below requirement in ASHRAE Standard 62-2001; 50 % are below that requirement based on the number of workstations.

As seen in Table 1, the outdoor air ventilation determined from the CO_2-ratio outdoor air fraction multiplied by the measured supply airflow are, on average, similar to the volumetric values. Figure 1 is a plot of the CO_2-ratio ventilation to the volumetric values. While there is scatter about the line of perfect agreement, and a tendency for the CO_2-ratio values to be lower at high rates, the two determinations are consistent on average. A linear regression of CO_2-ratio to the volumetric ventilation yields a slope of 0.78 and an r-squared of 0.81.

Table 1 also summarizes the outdoor air ventilation rates based on the peak indoor carbon dioxide concentrations. As noted earlier, this approach assumes that the indoor CO_2 concentration is at steady state, that the outdoor concentration, ventilation and occupancy are constant, and that the indoor CO_2 concentration is uniform. Note that the peak CO_2 values are significantly lower than those obtained using the other two methods. This trend is contrary to what might be expected, as the outdoor airflows determined using the peak CO_2 method include both ventilation system outdoor air intake and outdoor air infiltration due to envelope leakage, while the volumetric results include only the former. Figure 2 is a plot of the per person outdoor air ventilation determined from the peak CO_2 concentrations versus the corresponding volumetric values. The solid line corresponds to perfect agreement.

The reason that the peak CO_2 values tend to be lower than expected has been investigated, but no explanation has yet been verified. The lack of steady-state CO_2 concentrations could be an issue, but steady state is more likely to occur at the higher ventilation rates due to the shorter time constants. This effect would result in better agreement at higher rates, which is contrary to what is seen in Figure 2. Another potential explanation is the existence of significant CO_2 concentration gradients within the study spaces, as well as between them and adjoining spaces. While it is possible that the CO_2 concentrations were different in adjoining zones, one would expect the impact to be positive in some cases and negative in others. However, the differences tend to all be in one direction. Note also that the fixed CO_2 monitors were located 1.1 m above the floor and at locations representative of workstation layout and work activities, i.e., locations in hallways were avoided (EPA 2003). It is therefore possible that the measured concentrations are higher than the study-space average, which would lead to the calculated ventilation rates being low relative to their actual values. Also, it is reasonable to expect that the lack of uniformity would be more pronounced at higher outdoor air ventilation with less recirculation of return air, leading to the observed increased differences. However, it is not possible to verify the magnitude of the concentration nonuniformity based on the available data, and therefore it cannot be confirmed whether this is a valid explanation.

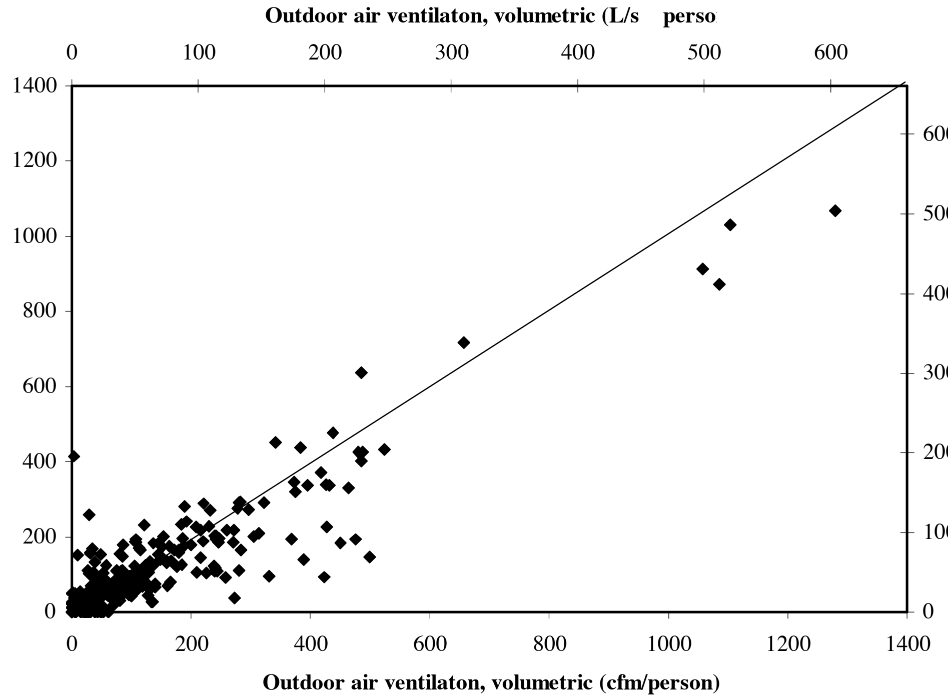

Figure 1. *Outdoor air ventilation, CO_2-ratio versus volumetric*

DISCUSSION

The volumetric ventilation rates determinations appear to yield reasonable values based on the system design values and outdoor air requirements in Standard 62, particularly after they are adjusted for the actual occupancy levels and the system outdoor air fractions. However, outdoor air intake traverse were sometimes impractical based on system configurations, such as very short lengths of intake ductwork or inaccessible ducts. In such cases, multiplying the measured supply airflow by the outdoor air fraction based on CO_2 concentrations in the supply, return and outdoor airstreams provided a good alternative. However, these outdoor air fractions, and the calculated outdoor airflows, were associated with large measurement uncertainties due to the uncertainty in the concentration measurement itself and the low concentration differentials that exist under some conditions. Nevertheless, this approach still has value based on the relative simplicity of measuring CO_2 concentrations. The CO_2 approach to determining outdoor air fraction could be improved by using a more accurate concentration monitor, employing the uncertainty in the differential concentration rather than absolute concentration (when a single monitor is used to measure the three concentrations), and making the concentration measurements after the indoor concentration has increased to the maximum degree expected based on the occupancy schedule.

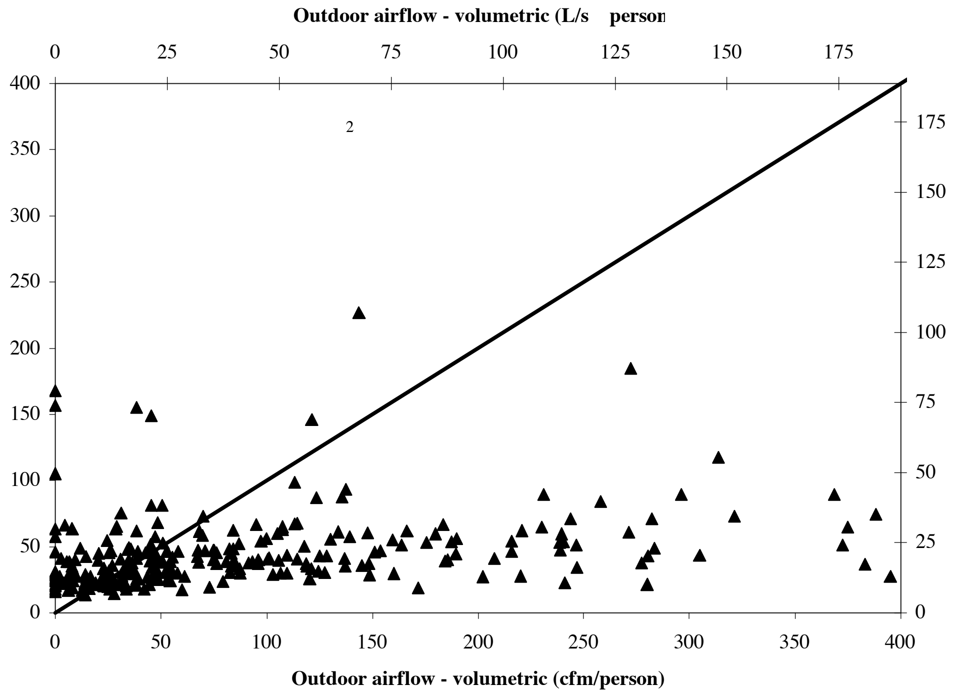

Figure 2. *Outdoor air ventilation, CO_2 peak versus volumetric*

The outdoor air ventilation estimated from peak CO_2 concentrations tended to be lower than those based on volumetric airflow measurements at the air handlers, and the reason for this difference is not evident. In fact, one would expect these values to be higher since they include envelope infiltration in addition to outdoor air intake. One potential explanation is that the concentrations measured in the space were elevated due to the influence of high CO_2 levels from occupant exhalations. The CO_2 data collected in the BASE study should be examined further to understand this discrepancy and potentially determine ways to improve this approach to estimate building ventilation. In addition, the reliability of the estimates of the generation rates of CO_2 from occupants and of the occupant activity or met levels used in making these estimates merits evaluation if this approach is going to be more widely used.

CONCLUSIONS AND IMPLICATIONS

The ventilation-related information collected as part of the BASE study provides a unique characterization of ventilation system design and performance in U.S. office buildings. No such database of randomly selected office buildings existed prior to this effort, making the results of the survey that much more significant. While the office buildings studied tend to be larger and with higher occupancy than the average U.S. office building, the results obtained are quite revealing.

The challenges in making reliable measurements of outdoor air intake rates is evident from this study. Some of the problems include limited access to system components, ductwork configurations that do not provide appropriate traverse planes, and accuracy limitations inherent in duct traverses. Alternative approaches to determining outdoor air intake at air handlers are being investigated and ideally will be more reliable and convenient for field application. One challenge in this respect is the lack of a primary standard for use in evaluating the accuracy of these various approaches.

ACKNOWLEDGEMENTS
This effort was supported by the U.S. EPA under Interagency Agreement No. DW-13-93936601-0, but was not subjected to the U.S. EPA's peer review. The conclusions in this paper are those of the authors and are not necessarily those of the U.S. EPA.

REFERENCES

Apte MG., Fisk WJ. and Daisey JM. 2000. “Associations Between Indoor CO2 Concentrations and Sick Building Syndrome Symptoms in US Office Buildings: An Analysis of the 1994-1996 BASE Study Data.” Indoor Air, 10 (4): 246-257.

ASHRAE. 2001. ANSI/ASHRAE Standard 62-2001, Ventilation for Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Brightman HS., Womble SE., Ronca EL. and Girman JR. 1996. “Baseline Information on Indoor Air Quality in Large Buildings (BASE '95).” Proceedings of 7th International Conference on Indoor Air Quality and Climate – Indoor Air ’96. Nagoya: Indoor Air ’96, Vol 3, pp 1033-1038.

EPA. 2003. “A Standardized EPA Protocol for Characterizing Indoor Air Quality in Large Office Buildings.” U.S. Environmental Protection Agency.

Erdmann CA., Steiner KC. and Apte MG. 2002. “Indoor Carbon Dioxide Concentrations and Sick Building Syndrome Symptoms in the BASE Study Revisited: Analyses of the 100 Building Dataset.” Proceedings of 9th International Conference on Indoor Air Quality and Climate – Indoor Air 2002. Monterey: Indoor Air 2002, Vol 3, pp 443-448.

Persily AK. 1997. “Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide.” ASHRAE Transactions, 103(2): 193-204.

Persily A. and Gorfain J. 2004. “Analysis of ventilation Data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) Study.” NISTIR 7145, National Institute of Standards and Technology (USA)

Womble SE., Girman JR., Ronca EL., Axelrad R., Brightman HS. and McCarthy JF. 1995. “Developing Baseline Information on Buildings and Indoor Air Quality (BASE '94): Part I - Study Design, Building Selection, and Building Description.” Proceedings of Healthy Buildings '95. Milan: Vol 3, pp 1305-1310.

Womble SE., Ronca EL., Girman JR. and Brightman HS. 1996. Developing Baseline Information on Buildings and Indoor Air Quality (BASE '95). Proceedings of ASHRAE IAQ 96. Paths to Better Building Environments, Baltimore: pp 109-117.